

# On the azimuthal asymmetries in DIS

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## Abstract

Using the recent experimental data on the left right asymmetry in fragmentation of transversely polarized quarks and the theoretical calculation of the proton transversity distribution in the effective chiral quark soliton model we explain the azimuthal asymmetries in semi-inclusive hadron production on longitudinally (HERMES) and transversely (SMC) polarized targets with no free parameters. On this basis we state that the proton transversity distribution could be successfully measured in future DIS experiments with *longitudinally* polarized target.

## 1 Introduction

Recently a first information about azimuthal asymmetries in semi inclusive hadron production on longitudinally (HERMES [1]) and transversely (SMC [2]) polarized targets was reported. These asymmetries contain information on the proton transversity distribution.

The three most important (twist-2) parton distributions functions (PDF) in a nucleon are the non-polarized distribution function  $f_1(x)$ , the longitudinal spin distribution  $g_1(x)$  and the transverse spin distribution  $h_1(x)$  [3]. The first two have been more or less successfully measured experimentally in classical deep inelastic scattering (DIS) experiments but the measurement of the last one is especially difficult since it belongs to the class of the so-called helicity odd structure functions and can not be seen there. To access these helicity odd structures one needs either to scatter two polarized protons or to know the transverse polarization of the quark scattered from transversely polarized target.

There are several ways to do this:

1. To measure a polarization of a self-analyzing hadron to which the quark fragments in a semi inclusive DIS (SIDIS), e.g.  $\Lambda$ -hyperon [4]. The drawback of this method however is a rather low rate of quark fragmentation into  $\Lambda$ -particle ( $\approx 2\%$ ) and especially that it is mostly sensitive to  $s$ -quark polarization.
2. To use a spin dependent T-odd parton fragmentation function (PFF) [5, 6, 7] responsible for the left-right asymmetry in one particle fragmentation of transversely polarized quark with respect to quark momentum–spin plane. (The so-called "Collins asymmetry" [8].)

- To measure a transverse handedness in multi-particle parton fragmentation [9], i.e. the correlation of the quark spin 4-vector  $s_\mu$  and particle momenta  $k^\nu$ ,  $\epsilon_{\mu\nu\sigma\rho} s^\mu k_1^\nu k_2^\sigma k^\rho$  ( $k = k_1 + k_2 + k_3 + \dots$ ).

The last two methods are comparatively new and only in the last years some experimental indications to the T-odd PFF have appeared [10, 11]. In this paper we will use this result to extract the information on the proton transversity distribution. More exactly with this result and the calculation of  $h_1(x)$  in the effective chiral quark soliton model [12], we compute the azimuthal asymmetries in SIDIS and compare it with the experimental points [1, 2]. A similar work was done recently in the paper [13] where the authors used some adjustable parametrization for the T-odd PFF and some estimations for  $h_1(x)$ . Our approach is free of any adjustable parameters.

In [14] it was shown that the chiral quark–soliton model possesses all features needed for a successful description of the nucleon parton structure: it is essentially a quantum field-theoretical relativistic model with explicit quark degrees of freedom, which allows an unambiguous identification of the quark as well as the antiquark distributions in the nucleon. Owing to its field-theoretical nature the quark and antiquark distributions obtained in this model satisfy all general QCD requirements: positivity, sum rules, inequalities, etc.

Analogous of  $f_1$ ,  $g_1$  and  $h_1$  are the functions  $D_1$ ,  $G_1$  and  $H_1$ , which describe the fragmentation of a non-polarized quark into a non-polarized hadron and a longitudinally or transversely polarized quark into a longitudinally or transversely polarized hadron, respectively<sup>1</sup>.

These fragmentation functions are integrated over the transverse momentum  $\mathbf{k}_T$  of a quark with respect to a hadron. With  $\mathbf{k}_T$  taken into account, new possibilities arise. Using the Lorentz- and P-invariance one can write in the leading twist approximation 8 independent spin structures [5, 6]. Most spectacularly it is seen in the helicity basis where one can build 8 twist-2 combinations, linear in spin matrices of the quark and hadron  $\boldsymbol{\sigma}$ ,  $\mathbf{S}$  with momenta  $\mathbf{k}$ ,  $\mathbf{P}_h$ .

Especially interesting is a new T-odd and helicity odd structure that describes a left–right asymmetry in the fragmentation of a transversely polarized quark:  $H_1^\perp \boldsymbol{\sigma}(\mathbf{k} \times \mathbf{P}_{h\perp})/k\langle P_{h\perp} \rangle$ , where the coefficient  $H_1^\perp$  is a function of the longitudinal momentum fraction  $z$  and quark transverse momentum  $k_T^2$ . The  $\langle P_{h\perp} \rangle$  is the averaged transverse momentum of the final hadron<sup>2</sup>.

Since the  $H_1^\perp$  term is helicity odd, it makes possible to measure the proton transversity distribution  $h_1$  in semi-inclusive DIS from a transversely polarized target by measuring the left-right asymmetry of forward produced pions (see [7, 15] and references therein).

The problem is that this function was completely unknown both theoretically and experimentally. Meanwhile, the data collected by DELPHI (and other LEP experiments) give a possibility to measure  $H_1^\perp$ . The point is that despite the fact that the transverse polarization of a quark (an antiquark) in  $Z^0$  decay is very small ( $O(m_q/M_Z)$ ), there is a non-trivial correlation between transverse spins of a quark and an antiquark in the Standard Model:  $C_{TT}^{q\bar{q}} = (v_q^2 - a_q^2)/(v_q^2 + a_q^2)$ , which reaches rather high values at  $Z^0$  peak:  $C_{TT}^{u,c} \approx -0.74$  and  $C_{TT}^{d,s,b} \approx -0.35$ . With the production cross section ratio  $\sigma_u/\sigma_d = 0.78$  this gives for the average over flavors a value of  $\langle C_{TT} \rangle \approx -0.5$ .

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<sup>1</sup>We use the notation of the work [5, 6, 7].

<sup>2</sup>Notice different normalization factor compared to [5, 6, 7],  $\langle P_{h\perp} \rangle$  instead of  $M_h$ .

The spin correlation results in a peculiar azimuthal angle dependence of produced hadrons, if the T-odd fragmentation function  $H_1^\perp$  does exist [8, 16]. A simpler method has been proposed recently by an Amsterdam group [6]. They predict a specific azimuthal asymmetry of a hadron in a jet around the axis in direction of the second hadron in the opposite jet<sup>3</sup>:

$$\frac{d\sigma}{d \cos \theta_2 d\phi_1} \propto (1 + \cos^2 \theta_2) \cdot \left( 1 + \frac{6}{\pi} \left[ \frac{H_1^{\perp q}}{D_1^q} \right]^2 C_{TT}^{q\bar{q}} \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_1) \right), \quad (1)$$

where  $\theta_2$  is the polar angle of the electron and the second hadron momenta  $\mathbf{P}_2$ , and  $\phi_1$  is the azimuthal angle counted off the  $(\mathbf{P}_2, e^-)$ -plane.

This asymmetry was measured [10] using the DELPHI data collection. For the leading particles in each jet of two-jet events, summed over  $z$  and averaged over quark flavors (assuming  $H_1^\perp = \sum_H H_1^{\perp q/H}$  is flavor independent), the most reliable value of the analyzing power is given by

$$\left| \frac{\langle H_1^\perp \rangle}{\langle D_1 \rangle} \right| = (6.3 \pm 2.0)\%, \quad (2)$$

with presumably large systematic errors<sup>4</sup>.

## 2 Azimuthal asymmetries

The T-odd azimuthal asymmetry in semi inclusive DIS  $ep \rightarrow e'\pi^\pm X$ , which was measured by HERMES consist of two sorts of terms (see [7] Eq. (115)): a twist-2 asymmetry  $\sin 2\phi_h$  and a twist-3 asymmetry  $\sin \phi_h$ . Here  $\phi_h$  is the azimuthal angle around the  $z$ -axis opposite to direction of virtual  $\gamma$  momentum in the Lab frame, counted from the electron scattering plane (see Fig. 1). The first asymmetry is proportional to the  $p_T$ -dependent transverse quark spin distribution in longitudinally polarized proton,  $h_{1L}^\perp(x, p_T)$ , while the second one contains two parts: one term is proportional to the twist-3 distribution function  $h_L(x)$  and the second one proportional to the twist-3 interaction dependent correction to the fragmentation function  $\tilde{H}_L$ . In what follows we will systematically disregard this interaction dependent correction such as correction  $\tilde{H}_L$  or  $\tilde{h}_L$ <sup>5</sup>.

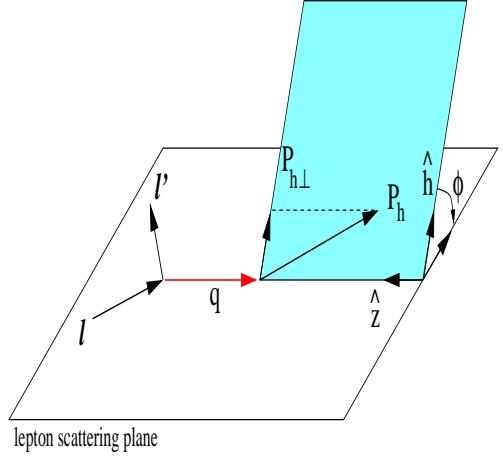
In the same approximation, the integrated functions over the quark transverse momentum,  $h_{1L}^\perp(x, p_T)$  and  $h_L(x)$ , are expressed through  $h_1$  (see [7] Eqs. (C15),(C19))

$$h_{1L}^{\perp(1)}(x) \equiv \int d^2 p_T \left( \frac{p_T^2}{2M^2} \right) h_{1L}^\perp(x, p_T) = -x^2 \int_x^1 d\xi h_1(\xi)/\xi^2 = -(x/2)h_L(x), \quad (3)$$

<sup>3</sup> We assume the factorized Gaussian form of  $P_{h\perp}$  dependence for  $H_1^{\perp q}$  and  $D_1^q$  integrated over  $|P_{h\perp}|$ .

<sup>4</sup> Close value was also obtained from pion asymmetry in inclusive  $pp$ -scattering [17].

<sup>5</sup> The calculations in the instanton model of QCD vacuum supports this assumption [18].



**Figure 1.** Kinematics of SIDIS in the Lab frame.

and the longitudinal spin dependent part of the SIDIS integrated over the modulus of the final hadron transverse momentum (assuming a Gaussian distribution) and over  $z$  reads as<sup>6</sup> (see [7] Eq. (115))

$$\begin{aligned} \frac{d\sigma_{UL}}{dxdydy} &= \frac{2\alpha^2 s}{Q^4} S_L \left[ \frac{2M}{\langle P_{h\perp} \rangle} \frac{1-y}{1+\frac{\langle p_T^2 \rangle}{\langle k_T^2 \rangle}} \sin 2\phi \cdot x^3 \sum_a e_a^2 \left( \int_x^1 d\xi h_1^a(\xi)/\xi^2 \right) \langle H_1^{\perp a/\pi}(z) \rangle \right. \\ &\quad \left. + \frac{M}{Q} \frac{4(2-y)\sqrt{1-y}}{\sqrt{1+\frac{\langle p_T^2 \rangle}{\langle k_T^2 \rangle}}} \sin \phi \cdot x^3 \sum_a e_a^2 \left( \int_x^1 d\xi h_1^a(\xi)/\xi^2 \right) \langle H_1^{\perp a/\pi}(z)/z \rangle \right], \end{aligned} \quad (4)$$

where  $M$  is the nucleon mass,  $S_L = S \cos \theta_\gamma \approx S(1-2M^2x(1-y)/sy) \approx S$  is longitudinal with respect to the virtual photon<sup>7</sup> part of the proton polarization  $S$ ,  $s = 2(Pl) = 2ME$  is the electron-proton c.m. total energy squared,  $Q^2 = sxy$  the modulus of the squared momentum transfer  $q = l-l'$ ,  $x = Q^2/2(Pq)$ ,  $y = 2(Pq)/s$ . The quantities  $\langle p_T^2 \rangle$  and  $\langle k_T^2 \rangle = \langle P_{h\perp}^2 \rangle/z^2$  are mean square values of the transverse momenta of the quark in distribution and fragmentation functions, respectively.

For the transverse part of the polarization and for the unpolarized target one can write (see [7] Eq. (110) with  $\phi_S = \pi$  and Eq. (113))

$$\frac{d\sigma_{UT}}{dxdydy} = \frac{2\alpha^2 s}{Q^4} S_T \frac{1-y}{\sqrt{1+\frac{\langle p_T^2 \rangle}{\langle k_T^2 \rangle}}} \sin \phi \cdot x \sum_a e_a^2 h_1^a(x) \langle H_1^{\perp a/\pi}(z)/z \rangle, \quad (5)$$

$$\frac{d\sigma_{UU}}{dxdydy} = \frac{2\alpha^2 s}{Q^4} \cdot \frac{1+(1-y)^2}{2} \cdot x \sum_a e_a^2 f_1^a(x) \langle D_1^{a/\pi}(z) \rangle, \quad (6)$$

where  $S_T = S \sin \theta_\gamma \approx S \sqrt{4M^2x(1-y)/sy}$  is the transverse part of the proton polarization.

The asymmetries measured by HERMES are

$$A_{UL}^W = \frac{\int d\phi dy W (d\sigma^+/S^+ - d\sigma^-/S^-)}{\frac{1}{2} \int d\phi dy (d\sigma^+/dx dy dy + d\sigma^-/dx dy dy)}, \quad (7)$$

where  $W = \sin \phi$  or  $\sin 2\phi$  and  $S_H^\pm$  is the nucleon polarization<sup>8</sup> ( $\pm$  sign means different spin directions with "+" means opposite to incident lepton beam), averaged over the transverse momentum  $P_{h\perp}$  and over  $z$  of the final  $\pi^+$  or  $\pi^-$  and  $\sigma = \sigma_{UU} + \sigma_{UL} + \sigma_{UT}$ .

Substituting (6), (4), (5) into (7) and integrating over the region of  $y$  allowed by the experimental cuts:

$$1 \text{ GeV}^2 \leq Q^2 \leq 15 \text{ GeV}^2, \quad W^2 = (P+q)^2 \geq 4 \text{ GeV}^2, \quad y < 0.85, \quad (8)$$

one can find the asymmetries  $A_{UL}^{\sin \phi}$  and  $A_{UL}^{\sin 2\phi}$  proportional to the ratios

$$\frac{\sum_a e_a^2 h_1^a(x) \langle H_1^{\perp a/\pi}(z)/z \rangle}{\sum_a e_a^2 f_1^a(x) \langle D_1^{a/\pi}(z) \rangle}, \quad (9)$$

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<sup>6</sup>Subscript  $U, L, T$  means unpolarized, longitudinally or transversely polarized beam or target respectively.

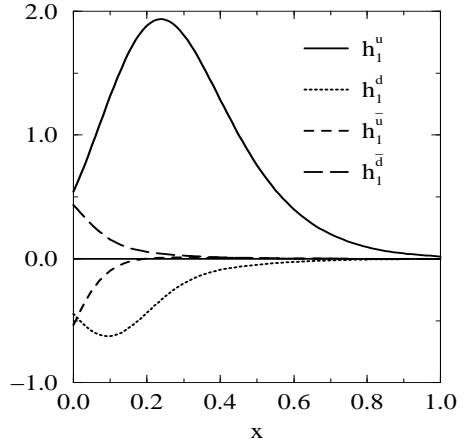
<sup>7</sup>Notice, that in HERMES experiment the target polarization was longitudinal with respect to the incident electron beam.

<sup>8</sup>More preferable would be the weights  $W = (P_{h\perp}/\langle P_{h\perp} \rangle) \sin \phi$  or  $(P_{h\perp}^2/M \langle P_{h\perp} \rangle) \sin 2\phi$  since the factors  $(1+\langle p_T^2 \rangle/\langle k_T^2 \rangle)$  in denominators of (4) and (5) would disappear.

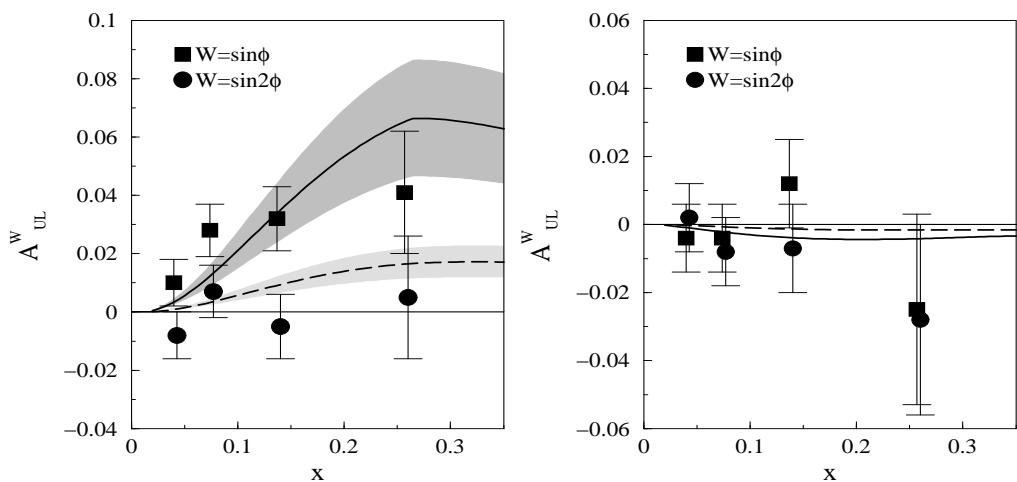
and

$$\frac{x^2 \sum_a e_a^2 \left( \int_x^1 d\xi h_1^a(\xi)/\xi^2 \right) \langle H_1^{\perp a/\pi}(z) \rangle}{\sum_a e_a^2 f_1^a(x) \langle D_1^{a/\pi}(z) \rangle}. \quad (10)$$

Let us assume that only the favored fragmentation functions  $D_1^{a/\pi}$  and  $H_1^{\perp a/\pi}$  will contribute this ratios, i.e.  $D_1^{u/\pi^+}(z) = D_1^{d/\pi^+}(z) = D_1^{d/\pi^-}(z) = D_1^{\bar{u}/\pi^-}(z) \equiv D_1(z)$  and similarly for  $H_1^\perp(z)$ . The dominance of the favored T-odd fragmentation is asserted also from Schäfer-Teryaev sum rule for these functions [19]. To explore the DELPHI result (2) we will use the approximation  $\langle H_1^\perp(z)/z \rangle = \langle H_1^\perp(z) \rangle / \langle z \rangle$  with the experimental values  $\langle z \rangle = 0.41$  and  $\langle P_{h\perp} \rangle \approx \langle p_T \rangle \approx 0.4 \text{ GeV}$  (see [20] and [21]). This would allow us to extract from the observed HERMES asymmetries an information on  $h_1^u(x) + (1/4)h_1^{\bar{d}}(x)$  and to compare with some model prediction. Instead, we use the prediction of the chiral soliton model for  $h_1^a(x)$  (see Fig. 2) and the GRV parametrization [22] of the unpolarized DIS data for  $f_1^a(x)$  to calculate the asymmetries  $A_{UL}^{\sin\phi}$  and  $A_{UL}^{\sin 2\phi}$  for  $\pi^+$  and  $\pi^-$ . The comparison of the asymmetries thus obtained with the HERMES experimental data is presented on Fig.3.



**Figure 2.** Transversity quark and antiquark distributions at a low normalization point ( $\mu \sim 600 \text{ MeV}$ ) in the effective chiral quark soliton model.



**Figure 3.** Single spin azimuthal asymmetry for  $\pi^+$  (left) and  $\pi^-$  (right):  $A_{UL}^{\sin\phi}$  (squares) and  $A_{UL}^{\sin 2\phi}$  (circles) as a functions of  $x$ . The solid ( $A_{UL}^{\sin\phi}$ ) and the dashed lines ( $A_{UL}^{\sin 2\phi}$ ) correspond to the chiral quark-soliton model calculation at  $Q^2 = 4 \text{ GeV}^2$ . The shaded areas on the left figure represent the experimental uncertainty in the value of the ratio  $|\langle H_1^\perp(z) \rangle / \langle D_1(z) \rangle|$ . For  $\pi^-$  (right) both asymmetries are compatible with zero.

The agreement is good enough though the experimental errors are yet rather large. Moreover the sign of the asymmetry is uncertain since only the modulus of the analyzing power (2) is known experimentally. However, Fig.3 gives evidence for positive sign. The theoretical

curves correspond to normalization point  $Q^2 = 4 \text{ GeV}^2$  although the  $Q^2$ -dependence of the asymmetries is very weak and do not exceeds 10% in the range (8). Notice that in spite of the factor  $M/Q$  the  $\sin \phi$  term in Exp. (4) is several times larger than that of  $\sin 2\phi$  for moderate  $Q^2$ . That is why this asymmetry prevails for the HERMES data where  $\langle Q^2 \rangle \approx 2.5 \text{ GeV}^2$ . One can thus state that the effective chiral quark soliton model [12] gives a rather realistic picture of the proton transversity  $h_1^a(x)$ .

The interesting observable related to  $h_1(x)$  is the proton tensor charge defined as

$$g_T \equiv \sum_a \int_0^1 dx (h_1^a(x) - h_1^{\bar{a}}(x)). \quad (11)$$

The calculation of  $g_T$  in this model yields for  $Q^2 = 4 \text{ GeV}^2$  [23]

$$g_T = 0.6. \quad (12)$$

The most recent experimental value of the proton axial charge is [24]

$$a_0 = 0.28 \pm 0.05, \quad (13)$$

and the value obtained in the model is  $a_0 = 0.35$  [25, 26]. We can conclude that the chiral quark soliton model predicts very different values for the axial and tensor charges of the nucleon, which is in contradiction with the nonrelativistic quark model prediction.

Concerning the asymmetry observed by SMC [2] on transversely polarized target one can state that it agrees with result of HERMES. Really, SMC has observed the azimuthal asymmetry  $d\sigma(\phi_c) \propto \text{const} \cdot (1 + a \sin \phi_c)$ , where  $\phi_c = \phi_h + \phi_S - \pi$  ( $\phi_S$  is the azimuthal angle of the polarization vector) is the so-called Collins angle. The raw asymmetry  $a = P_T \cdot f \cdot D_{NN} \cdot A_N$ , where  $P_T$ ,  $f$ , and  $D_{NN} = 2(1-y)/[1+(1-y)^2]$  are the target polarization value, the dilution factor and the spin transfer coefficient.

The physical asymmetry  $A_N$ , averaged over transverse momenta (assuming again a Gaussian form) is given by expression (9) divided by  $\sqrt{1 + \langle p_T^2 \rangle / \langle k_T^2 \rangle}$ . With the same functions  $h_1^a(x)$ ,  $f_1^a(x)$ , integrating over  $x$  separately the numerator and the denominator weighted by  $xQ^{-4}$ , we get for  $Q^2 = 4 \text{ GeV}^2$  with error due to (2) (see Fig. 4)

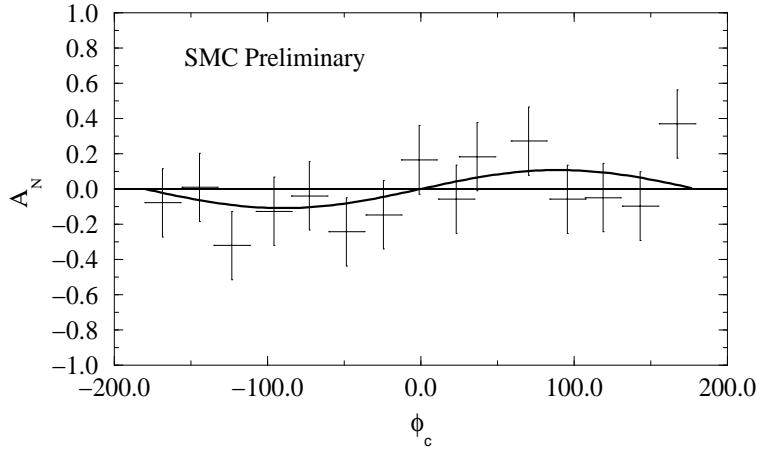
$$A_N = 0.07 \pm 0.02, \quad (14)$$

which should be compared with the experimental best fit value  $A_N = 0.11 \pm 0.06$ .

### 3 Conclusions

In conclusion, using the effective chiral quark soliton model for the proton transversity distribution we obtain a rather good description of the azimuthal asymmetries in semi-inclusive hadron production measured by HERMES and SMC, though the experimental errors are yet large. This, however is only the first experiment! We would like to stress that our description has no free adjustable parameters.

Probably the most useful lesson we have learned is that to measure transversity in SIDIS in the region of moderate  $Q^2$  it is not necessary to use a transversely polarized target. Due to approximate Wandzura-Wilczek type relations (3) one can explore the longitudinally polarized target also. This is very important for future experiments, like COMPASS at CERN



**Figure 4.** Collins angle  $\phi_c$  azimuthal distributions for positive hadrons produced off transversely polarized protons. The solid line is the curve  $0.07 \sin \phi_c$ , obtained in the chiral quark-soliton model.

since the proton transversity measurements could be done simultaneously with measurement of the spin gluon distribution  $\Delta g(x)$ . For a better interpretation of the result a better knowledge of quark analyzing power (2) with smaller systematic errors is necessary.

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